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REPORT

RELATIVE ROLES OF GRAVITATIONAL
AND INERTIAL WORK IN THE ENERGY
COST OF HUMAN LOCOMOTION

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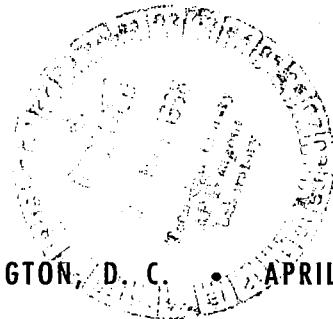
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SUMMARY

The metabolic cost of walking was measured during walking on the tread-
mill at various slopes - positive, level and negative - and before and after
loading of the principal body segments.

An equation derived from these studies relates metabolic demand to
speed of walking under 1/6 g conditions, and is shown to be in acceptable
agreement with the data obtained by other investigators for moderate speeds
of walking under simulated 1/6 g conditions.

The effects of load upon the metabolic cost of walking are shown to be
critically dependent upon the segment of the body loaded. Loading of the
extremities causes a much greater increase in the metabolic cost of walking
than loading of the trunk, due to the greater magnitude of inertial (kinetic
energy) work compared with gravitational work.

The probable metabolic effects of restraint of free body motion, com-
bined with difficult terrain, are briefly discussed.

INTRODUCTION

The metabolic cost of human locomotion is primarily due to two inter-
locking types of work: (1) The work of raising the body in the earth's
gravitational field; (2) The work involved in accelerating and decelerating
the various segments of the body. During a single step, there is an ex-
tensive transfer of energy, potential or kinetic, from one body segment to
another, so that the total metabolic cost of walking is much less than it
would be if the body did not behave as a semiconservative system.

Fortunately, as has been shown by Bresler and Berry (1), certain
motions of body segments at normal level walking speeds involve such small
energy changes that they may be neglected. These include lateral and
rotational motions of the HAT (head + arms + trunk), rotational motions of
the limb segments, and arm swing. Changes in potential energy of the limb

segments are also of small magnitude, and may be corrected for with the use of data provided by Bresler and Berry. An adequate analysis, therefore, requires only consideration of changes in potential energy and kinetic energy of translation of the HAT, and changes in kinetic energy of translation of the limb segments.

At the surface of the earth, it is not possible by any direct means to eliminate the role of the earth's gravitational field in the energy demands of walking. However, conditions simulating low gravity may be achieved by suspension of the body during inclined plane walking (Hewes, 2) and such studies have provided important information for anticipating the metabolic demands of walking in a weak gravitational field.

The present investigation aims to separate gravitational from inertial factors by (1) use of walking on the treadmill at moderate positive and negative slopes, and (2) loading of various segments of the body combined with a detailed analysis of the changes in potential and kinetic energy of body segments during a walking cycle. Some of the results of these studies will be compared with the results of the suspension studies mentioned above.

Finally, some remarks will be made regarding effects of restraint on body motions, and of terrain, on the metabolic cost of locomotion.

SYMBOLS, ABBREVIATIONS, AND EQUIVALENTS

B   Body weight, kg

g   Acceleration due to gravity at earth's surface

$\dot{Q}$ Energy expenditure, kcal/min (1000 Btu/hr = 4.2 kcal/min)

$\dot{q}$ Small cal/min/kg (1 Btu/hr/lb = 9.25 cal/min/kg)

v   Speed m/min (1 mph = 26.8 m/min)

$\dot{v}_{O_2}$ Oxygen used, ml/min, standard conditions

$\dot{V}_{O_2}$ Oxygen used, liters/min, standard conditions (1 liter oxygen used corresponds approximately to 5 kcal or 20 Btu)
         (1 liter oxygen used per minute corresponds approximately to 5 kcal/min or 1200 Btu/hr)

$\dot{W}$ Lift-work, kg-m/min (1 Btu = 107 kg-m)

$\dot{Z}_h$ Apparent (hill, topographical) vertical lift, m/min

$\dot{Z}_T$ True vertical lift, m/min

1. Slope Walking on the Treadmill

The metabolic cost of level floor walking, at speeds ranging from about 25 to 100 m/min, corresponding to cadences of about 60 to 120 steps/min, was shown by Ralston (3) to be a linear function of v^2, and expressed by

$$\dot{q} = 0.0053v^2 + 29 \tag{I}$$

The same author also showed (4) that treadmill walking yielded similar results, provided that the subjects wore light, rubber-soled shoes.

It is a common experience that downhill walking is less demanding than uphill walking, at least for moderate slopes. We have found that at speeds of about 75 m/min, and at slopes of $+2^o$ and -2°, the values of $\dot{q}$ are of the order of 20% above and below, respectively, those of level walking. At slopes ranging from about $+4^o$ to -4°, there is little effect on the posture of the body at moderate walking speeds, and no measurable effect upon the cadence for a given speed.

It has been commonly assumed by previous investigators that the increased metabolic cost of positive slope walking may be interpreted simply in terms of the "hill" height (apparent height, topographical height) climbed in a certain interval of time. However, in the present experiments the vertical motion of the body in space is measured by a transducer attached to a belt at the approximate center of mass of the body. The vertical component due to motion of the treadmill itself is added to, or subtracted from the measured motion in space, depending upon whether the subject is walking uphill or downhill. In this way, the true vertical lift of the body, due to muscular effort, in any given period, is determined.

The "hill" height per minute, $\dot{Z}_h$, and the true vertical lift, $\dot{Z}_T$, are shown in fig. 1, as mean values for three subjects walking at three different speeds, and at grades ranging from $+4^o$ to -4°. The striking difference between $\dot{Z}_h$ and $\dot{Z}_T$ is evident, and it is clear that any analysis of the relation between vertical lift and metabolic demand must be based upon $\dot{Z}_T$ and not $\dot{Z}_h$. (An exception to this occurs with very steep grades, where $\dot{Z}_T$ and $\dot{Z}_h$ approach each other, as shown for the highest values of lift-work in fig. 2.)

In fig. 2 are shown the relations between true lift-work per minute ($\dot{Z}_T$ x B), apparent lift-work per minute ($\dot{Z}_h$ x B), and oxygen consumption. The straight line has the equation

$$\dot{v}_{O_2} = 2.16\dot{W} + 300 \tag{II}$$

where $\dot{W}$ is the lift-work per minute.

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It is of some interest that this is the regression line for the data of Silverman (5) relating oxygen consumption to work on the bicycle ergometer.

Equation (II) may be rewritten

$$\dot{Q} = 0.0108\dot{W} + 1.50 \tag{III}$$

For a standard man weighing 70 kg, equation (I) becomes

$$\dot{Q} = 0.000371v^2 + 2.03 \tag{IV}$$

Eliminating $\dot{Q}$ between equations (III) and (IV) yields

$$\dot{W} = 0.0344v^2 + 49 \tag{V}$$

Fig. 3 shows the relation between lift-work and v^2 in six subjects. The equation of the straight line is

$$\dot{W} = 0.0407v^2 + 50 \tag{VI}$$

Averaging coefficients in (V) and (VI) yields

$$\dot{W} = 0.0375v^2 + 49.5 \tag{VII}$$

and $\dot{W}/6$ becomes

$$\dot{W}/6 = 0.0062v^2 + 8.2 \tag{VIII}$$

where $\dot{W}/6$ is the lift-work under 1/6 g conditions, assuming all other parameters to be unchanged.

Substituting $\dot{W}/6$ for $\dot{W}$ in equation (III) yields

$$\dot{Q} = 6.75 \times 10^{-5}v^2 + 1.59 \tag{IX}$$

The relation between $\dot{Q}$ and v, calculated from equation (IX), is shown as the lower solid curve of fig. 4. This curve, which ventures to predict the metabolic cost of walking under 1/6 g conditions, may be compared with the lower broken curve of fig. 4, which has been redrawn from Hewes (2), based upon simulated 1/6 g experiments on two subjects. The two curves are in acceptable agreement for speeds up to about 70 m/min, corresponding to cadences up to about 100 steps/min.

The upper broken curve, also from Hewes (2), shows the effect of a suit pressurized to 3.5 psi (plus 72 lb back-pack) upon the metabolic demand of walking. For moderate speeds, this curve is substantially the

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same as the upper solid curve, calculated from equation (I) for a standard man of 70 kg. At moderate speeds, the effect of the restraint offered by 3.5 psi is about the same as that produced by increasing the lift-work 6-fold. The very great role played by restraint in the metabolic cost of walking was studied by Ralston and colleagues (6) and will be briefly discussed in a later section.

The constant 29 in equation (I) was shown by Ralston (3) to be approximately the cost of very slow walking. The cost of quiet (but not completely immobile) standing was found by the same author to average $\dot{q} = 20$, which for a standard man would be $Q = 1.4$. This is only about 15% greater than the cost of resting in the supine position. The bottom two curves of fig. 4 indicate that for moderate speeds the effect of reducing the gravitational work of walking by the factor 6 would result in a metabolic demand scarcely greater than that of quiet standing at the surface of the earth. Unfortunately, however, the effects of restraint by either a soft or a hard suit are to nullify this advantage.

2. Effects of Load

Loading of the body increases the metabolic cost of walking, but the effects are very dependent upon the nature of the loading. Loads placed upon the distal segments, especially the foot, have relatively much greater effect than loads attached to the trunk, due to the large inertial effects associated with acceleration and deceleration of the limb segments.

Fig. 5, bottom, shows the effect of 2 kg on each foot upon the metabolic cost of walking at $+2^o$, 0°, and -2°. At 0°, the value of $\dot{q}$ is increased by about 30%, with similar results at $+2^o$ and -2°. This is to be contrasted with the very small effect of 5 kg attached to the trunk, where in 7 subjects the mean increase in $\dot{q}$ was only 4%.

A comparable experiment on shank loading is shown in fig. 6.

Unfortunately, this type of experiment is not entirely clear-cut, since, unexpectedly, the vertical motion of the body is also increased by loads on the extremities, as shown in the upper parts of figs. 5 and 6. As a consequence of this, both inertial and gravitational effects are involved when the extremities are loaded.

Figs. 7 - 9 show, in a much more definitive way, the effects of trunk vs. foot loading. The vertical scale in each figure shows the actual values of the mechanical energy levels of each body segment, measured in small calories, during a walking cycle. Potential and kinetic energies of the HAT, and kinetic energies of each limb segment (with corrections for

the relatively small potential energy changes) are calculated for 0.02 sec intervals, from motions recorded by transducers appropriately attached to trunk, thigh, shank and foot. Masses of body segments are determined from volumetric displacement and values of specific gravity available in the literature.

The subject of fig. 7 was a normal young female weighing 59 kg. The top curve, labeled "Body Total," shows the instantaneous mechanical energy level of the body as a whole during a walking cycle. The lower curves are corresponding curves showing total energies, kinetic energies, or potential energies, for each segment, as labeled.

Fig. 8 shows a similar set of curves for the same subject walking at the same speed as in fig. 7, but wearing a vest weighing 10 kg.

Fig. 9 shows the results of 2 kg attached to each foot.

A striking feature of these curves is the relative flatness of the "HAT Total" curves. This is due to the fact that the "HAT Horizontal Kinetic" and "HAT Potential" curves are approximate mirror images of each other, suggesting a transfer of energy as in a conservative system.

In spite of the considerable load imposed upon the trunk in the experiment of fig. 8, amounting to 17% of the body weight, and 28% of the HAT weight, there was only a modest increase of about 5% in the metabolic cost of walking, compared with the control experiment. This is reflected in the small increase in "Body Total," amounting to about 7%. It is clear that the principal factor in the change in energy cost of walking when there is a substantial increase in the mass of the trunk is the increase in gravitational work performed. However, even under conditions of earth gravity the effects of loading the trunk to a limit approaching the subject's tolerance are relatively modest in respect to mechanical work and metabolic cost.

The metabolic cost of trunk-loading in quiet standing is practically nil. As previously stated, the $\dot{q}$ for quiet standing under 1 g conditions is about 20. In an experiment on a young male subject weighing 64 kg the $\dot{q}$ of standing was not measurably altered by attaching 20 kg uniformly around the trunk. It may be stated with confidence that standing quietly under 1/6 g conditions will present no metabolic problem even when the body is heavily loaded by earth standards.

Turning to the experiment of fig. 9, it is obvious that the effect of foot-loading is in marked contrast to that of trunk-loading. Here the metabolic cost of walking was increased by about 30% over control, associated with a 35% increase in "Body Total." The striking feature of this experiment is the large increase in the "Leg Total," mainly due to kinetic

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energy changes of the foot. It is this inertial factor which accounts for the relatively large effect of limb-loading compared with trunk-loading on the metabolic cost of walking.

Studies of the type just described show that the inertial effects of limb-loading on metabolic cost of walking may be expected to be of critical importance whether under 1 g or 1/6 g conditions, while the effects of trunk-loading are relatively modest even under 1 g conditions.

3. Effects of Restraint and Terrain

Ralston and colleagues (6) studied the effect of restricting motion at ankle, knee, hip and spine on the metabolic cost of walking at moderate speeds. As a rough rule-of-thumb, it could be stated that immobilization of both ankles, or of one knee, or of one hip, or of the spine, would increase the metabolic cost of walking by about 10%. Almost certainly, though not studied, the effect of immobilization at several joints simultaneously would compound the metabolic demand. The marked effect shown by the 3.5 psi curve of fig. 4 is entirely consistent with the results of our immobilization studies.

The experiments described in this report have not involved the possible effect produced on the metabolic cost of walking by irregular or soft terrain. Passmore and Durnin (7), in their review of energy expenditure, state that "The type of surface may have a slight effect on the energy cost of walking. However, unless the surface is markedly rough, the effect will probably not exceed 10% more than walking on a flat surface." However, their table 3 shows an increase of about 35% for a subject walking at a speed of 90 m/min on ploughed field compared with asphalt road. Strydom et al. (8) in a recent study on 11 young men found that the metabolic cost of walking at about 80 m/min with loads of about 23 kg was 80% greater on loose sand than on a hard surface.

In both cases cited, the walking speed was fairly brisk, and therefore the results might not be very relevant to the effect of loose soil at lower speeds of walking. However, the compounding of restraint at joints, produced by either a soft or hard space suit, with difficult terrain, may be expected to have a very significant effect on the metabolic demand of walking. More studies on this matter are needed.

REFERENCES

1. Bresler, Boris, and Berry, F. R.: Energy and Power in the Leg During Normal Level Walking. Prosthetic Devices Research Project, Institute of Engineering Research, University of California, Berkeley, ser. 11, iss. 14, May 1951.

2. Hewes, Donald E.: Evaluation of a Gravity-Simulation Technique for Studies of Man's Self-Locomotion in Lunar Environment. NASA TN D-2176, 1964.

3. Ralston, Henry J.: Energy-speed relation and optimal speed during level walking. Int. Z. Angew. Physiol., 17:277-283, 1958.

4. Ralston, Henry J.: Comparison of energy expenditure during treadmill walking and floor walking. J. Appl. Physiol., 15:1156, 1960.

5. Silverman, Leslie; Lee, George; Plotkin, Theodore; Sawyers, Leonore A.; and Yancey, Anne R.: Air flow measurements on human subjects with and without respiratory resistance at several work rates. A.M.A. Arch. Industr. Hyg. Occ. Med., 3:461-478, 1951.

6. Ralston, Henry J.: Effects of immobilization of various body segments on the energy cost of human locomotion. Proc. 2nd I. E. A. Conference, Dortmund, 1964. [Supplement to] Ergonomics, pp. 53-60, 1965.

7. Passmore, R., and Durnin, J. V. G. A.: Human energy expenditure. Physiol. Rev., 35:801-840, 1955.

8. Strydom, N. B.; Bredell, G. A. G.; Benade, A. J. S.; Morrison, J. F.; Viljoen, J. H.; and van Graan, C. H.: The metabolic cost of marching at 3 m.p.h. over firm and sandy surfaces. Int. Z. Angew. Physiol., 23:166-171, 1966.
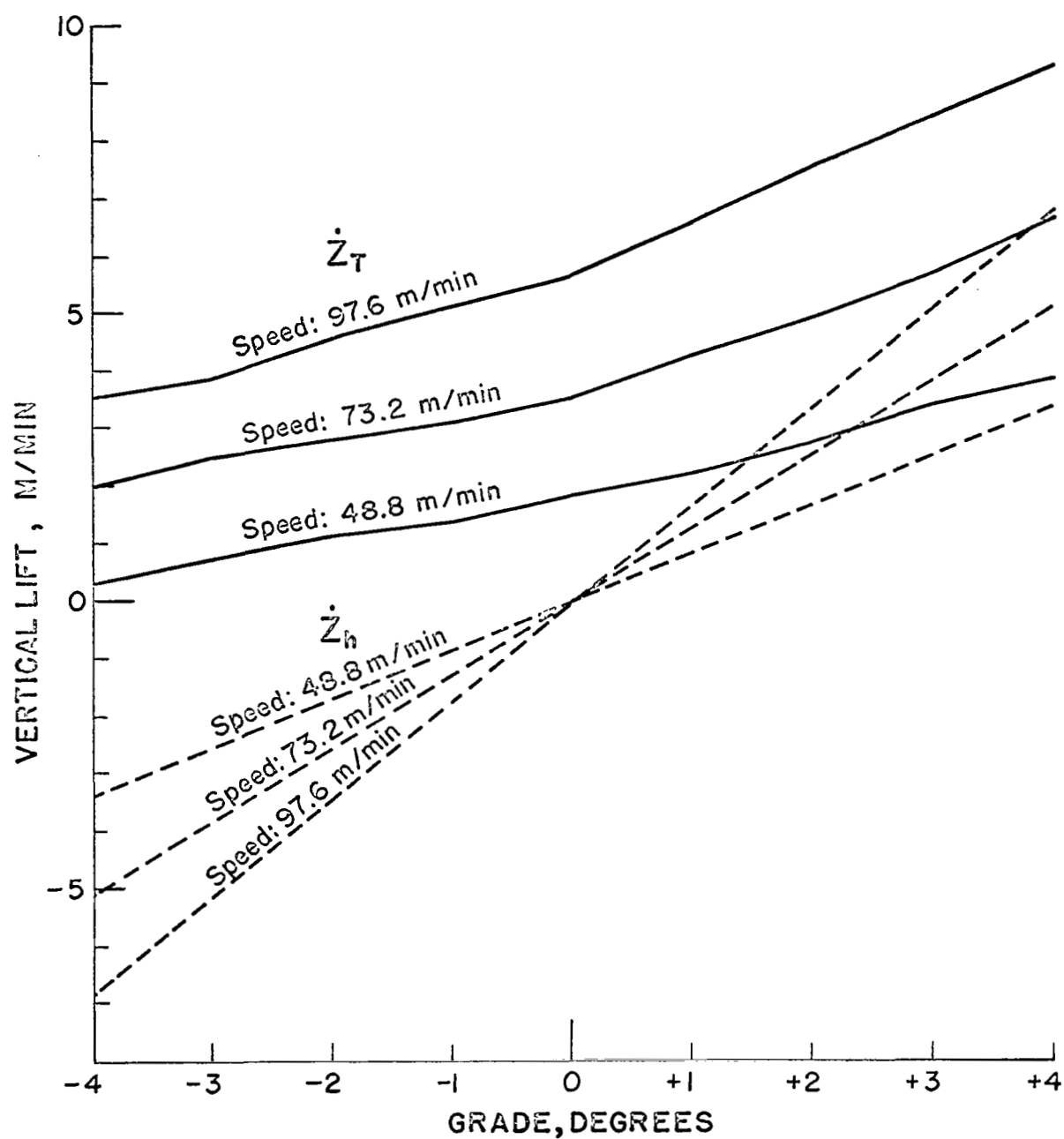
Fig. 1   Apparent (hill, topographical) vertical lift, $\dot{Z}_h$, and true vertical lift, $\dot{Z}_T$, for various grades and speeds.
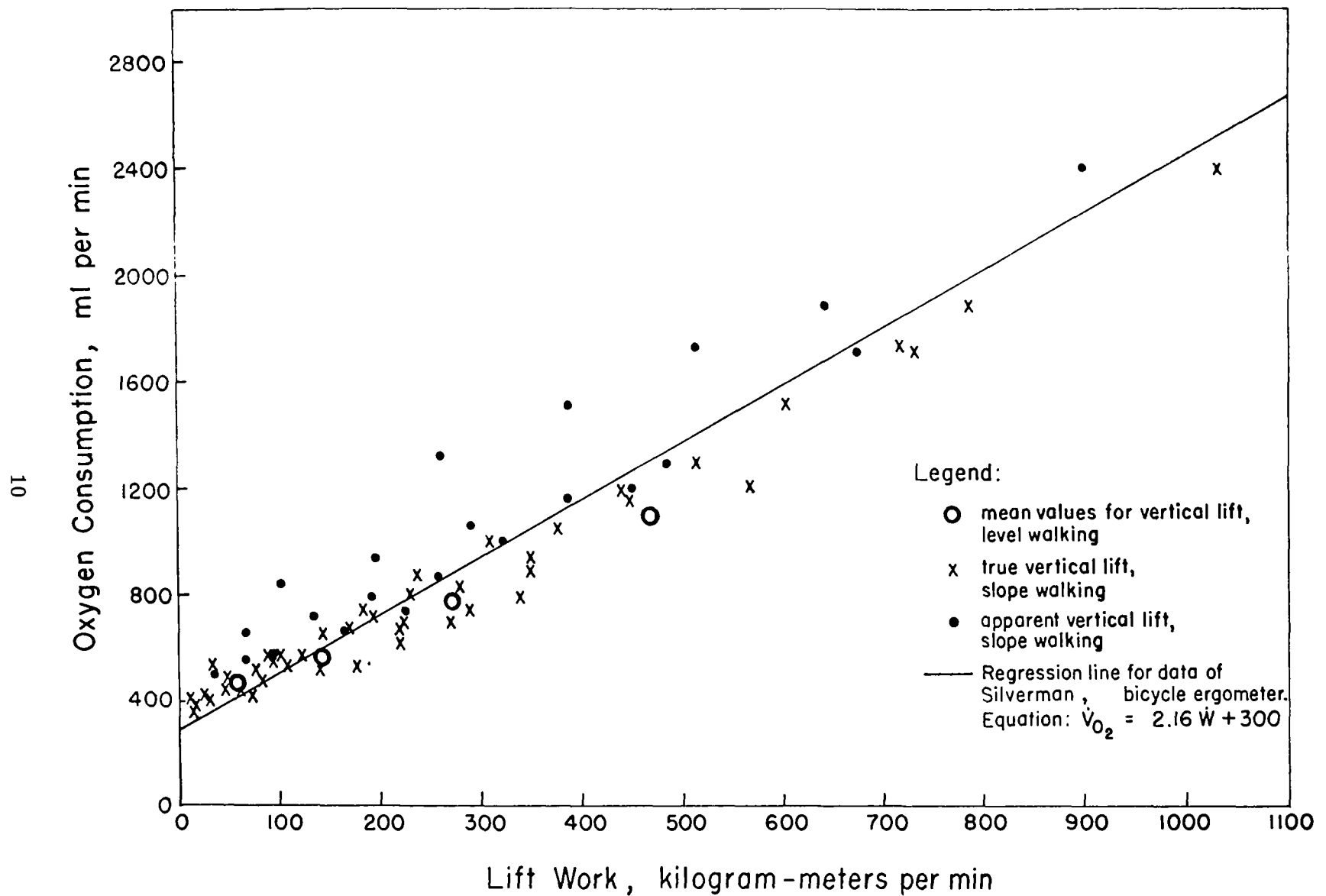
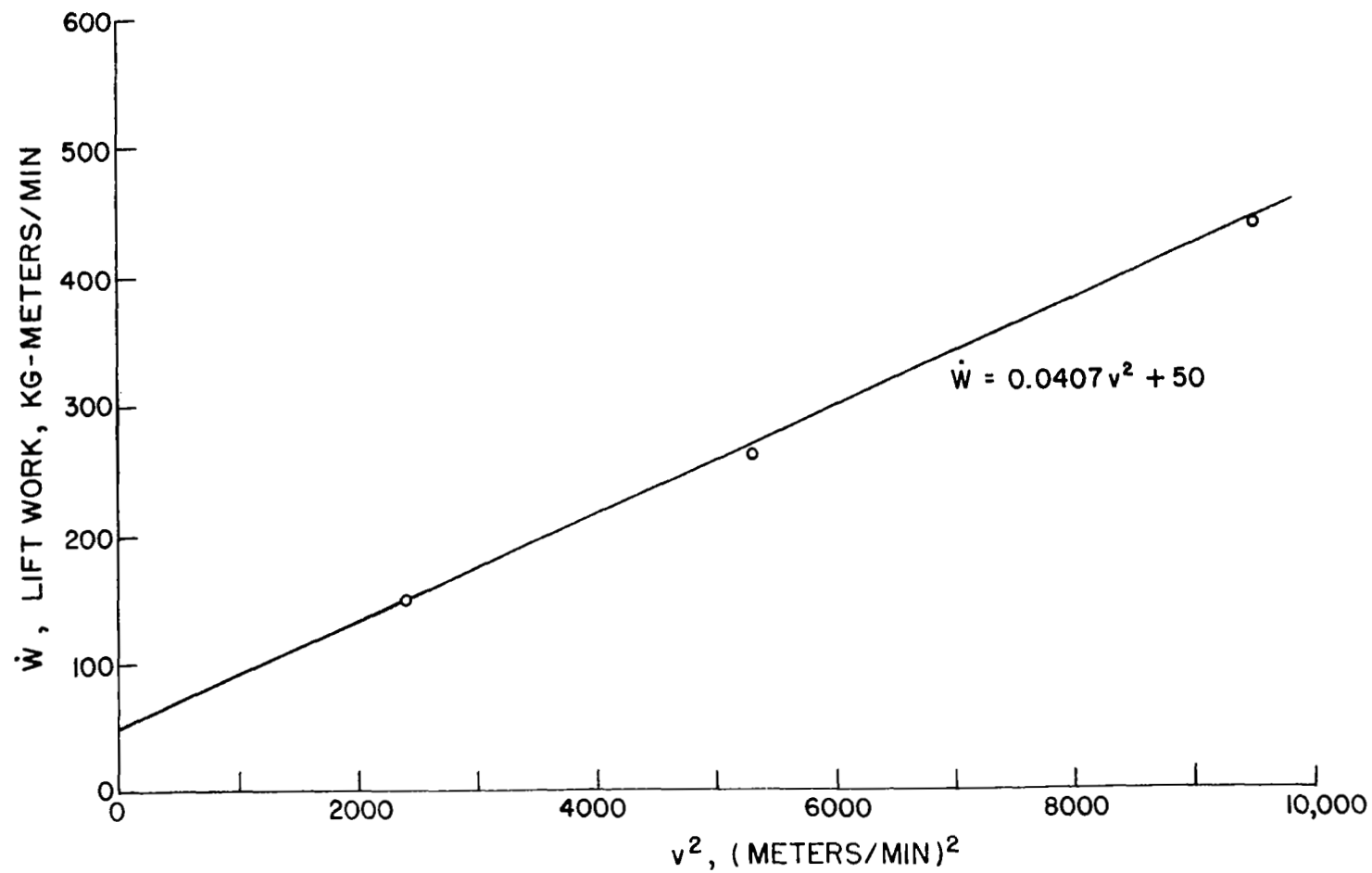Fig. 2   Metabolic cost in relation to true and apparent lift-work.

Fig. 3 Lift-work as a function of v^2 in level walking: Six subjects, mean values, speeds: 48.8, 73.2, and 97.6 m/min.
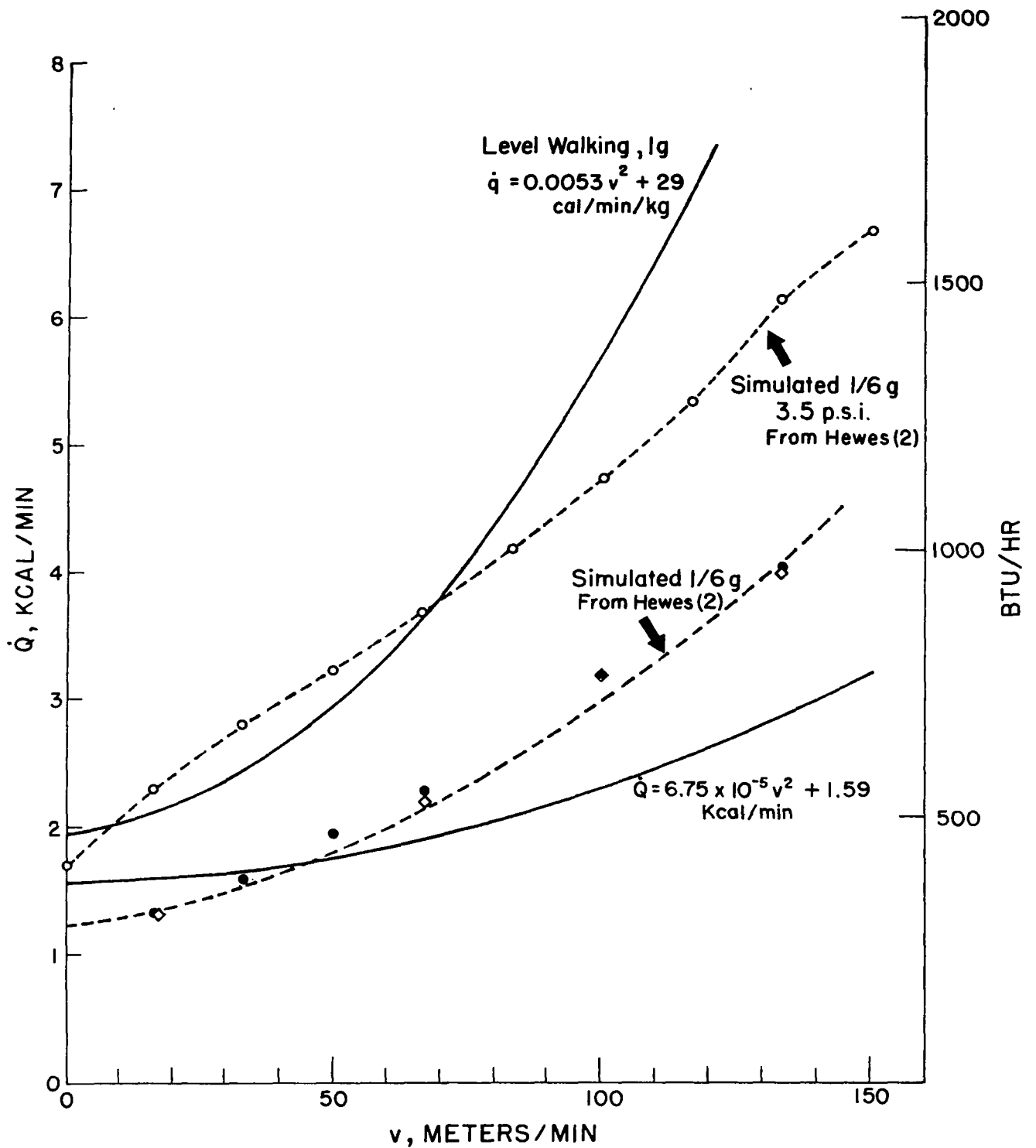
Fig. 4   Energy expenditure as a function of speed. Top to bottom:
normal level walking; simulated 1/6 g, pressurized suit;
simulated 1/6 g, normal clothing; prediction based on slope
walking. See text for discussion.

SUBJECT N.D., MALE
SPEED: 73.2 METERS/MIN
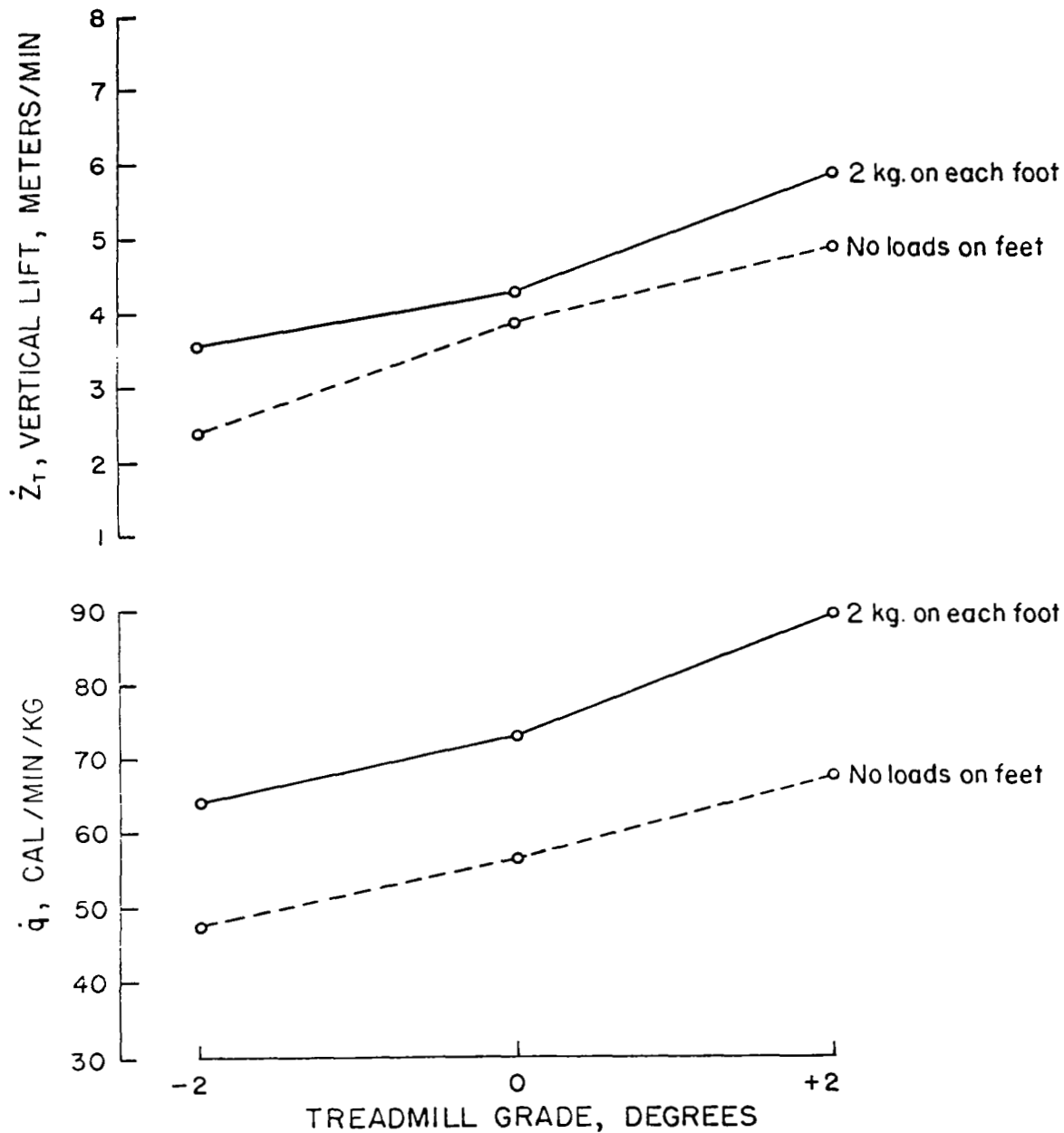
Fig. 5   Above: true vertical lift as a function of load on foot and
         of slope. Below: energy expenditure for same conditions.
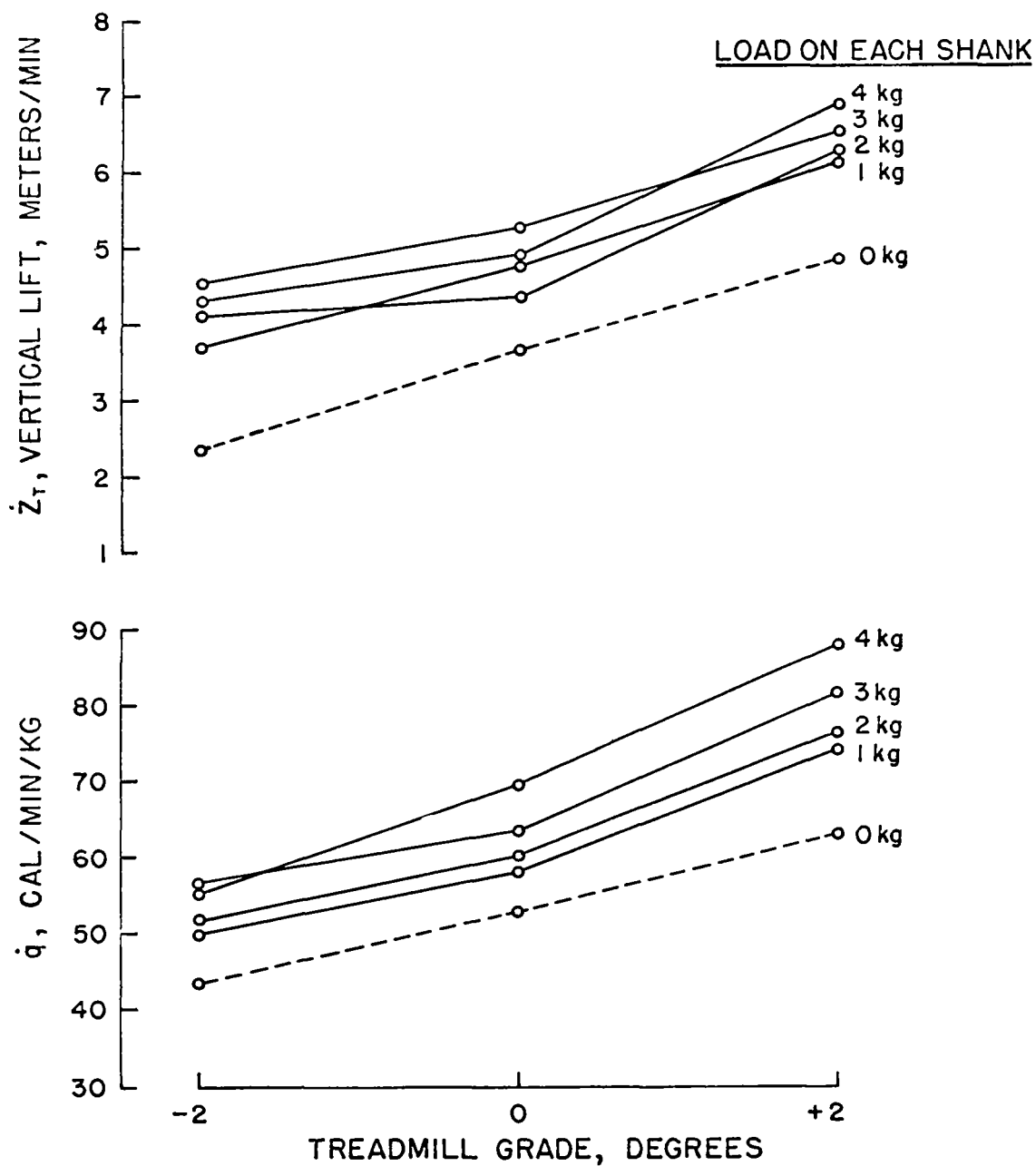
Fig. 6   Above: true vertical lift as a function of load on shank and
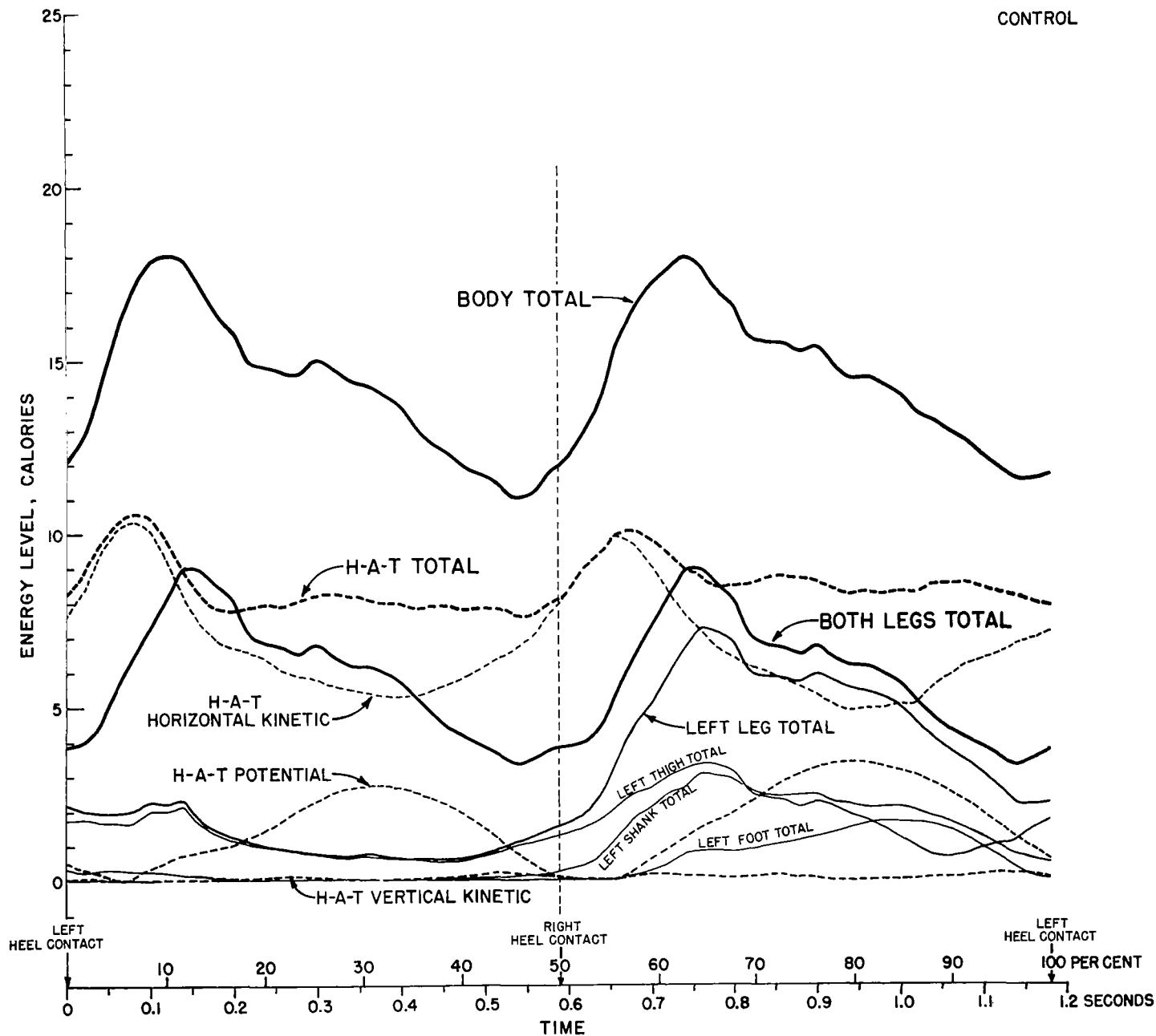slope.   Below: energy expenditure for same conditions.

Fig. 7   Mechanical energy levels of various body segments and whole
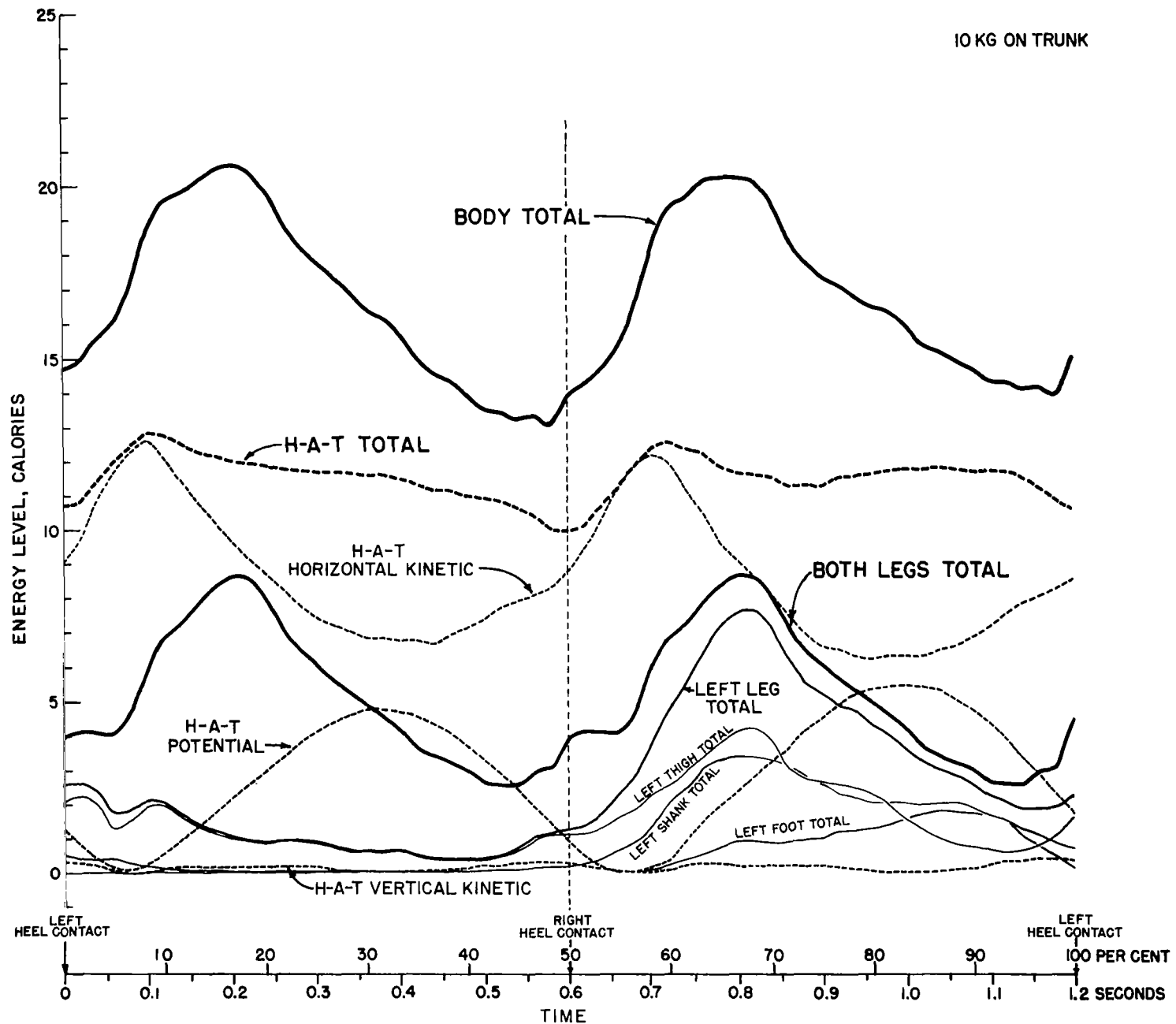body. Control. See text for discussion.

Fig. 8   Mechanical energy levels of the whole body.   Load of 10 kg on
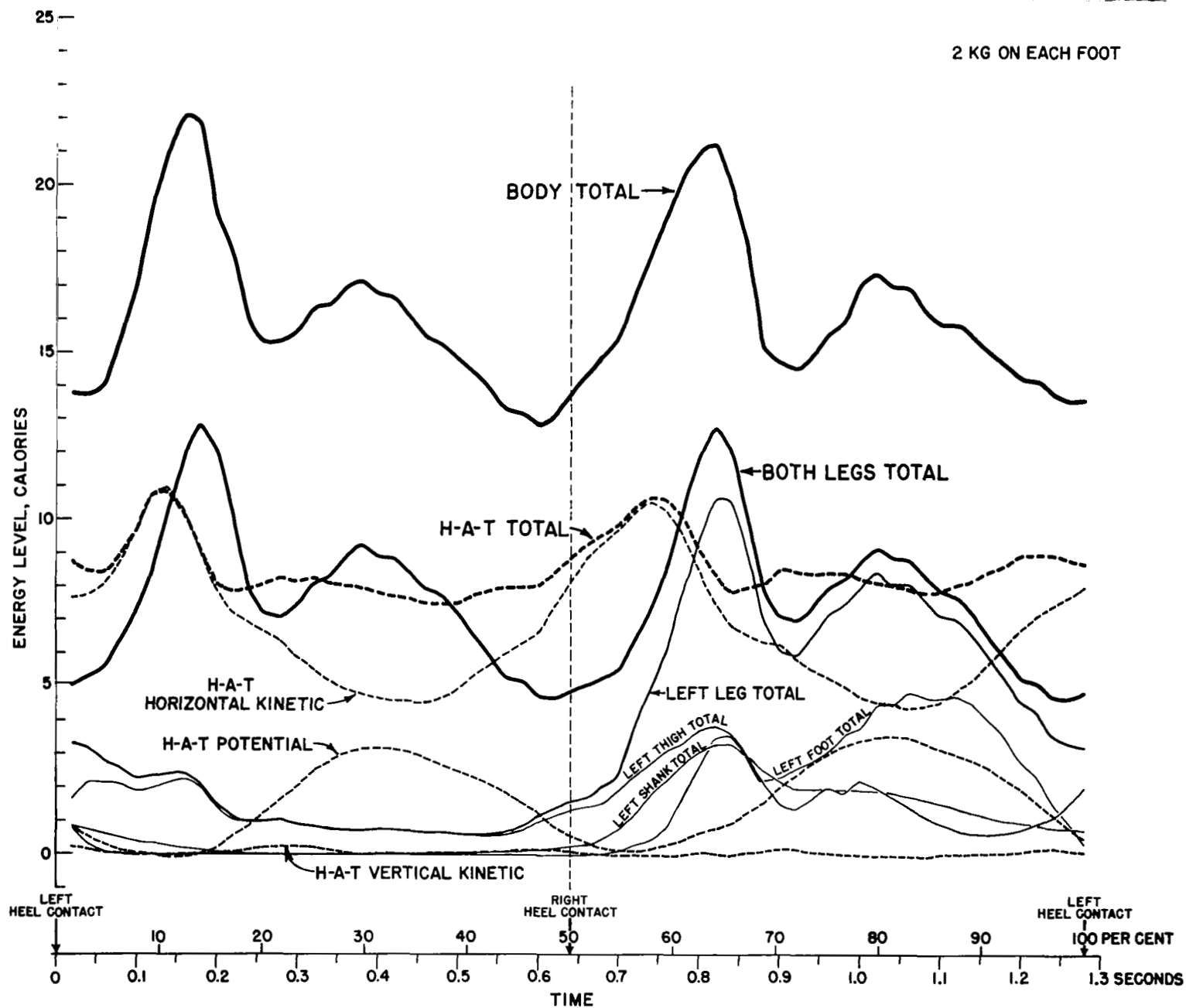trunk.   See text for discussion.

Fig. 9   Mechanical energy levels of various body segments with load
of 2 kg on each foot. See text for discussion.